Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2015/078

Maritimes Region

Species at Risk criteria and seismic-survey noise thresholds for cetaceans

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December 2015

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Theriault, J.A. and Moors-Murphy, H.B. 2015. Species at Risk criteria and seismic survey noise thresholds for cetaceans. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/078. v + 42 p.

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ABSTRACT

Mitigation measures are required for seismic survey operations occurring in Canadian waters to reduce potential negative effects on marine mammals. Since 2008, the statement of Canadian practice with respect to the mitigation of seismic sound in the marine environment (SOCP) has been used to guide the minimum standard mitigation measures recommended for seismic operations in Canadian waters. As an understanding of anthropogenic impacts and Canadian legislation evolves, it is necessary to revisit the policies and protocols intended to minimize such impacts. This research document strives to address if quantitative acoustic thresholds can be recommended to meet the needs of listed cetacean species protected by the Species at Risk Act (SARA). Where quantitative acoustic thresholds are not available, qualitative thresholds are discussed.

Critères des espèces en péril et seuils des niveaux de bruit des levés sismiques pour les cétacés

RESUME

Des mesures d'atténuation sont requises pour les activités de levés sismiques dans les eaux canadiennes afin de réduire les effets nocifs potentiels sur les mammifères marins. Depuis 2008, l'Énoncé des pratiques canadiennes d'atténuation des ondes sismiques en milieu marin [ci-après l'Énoncé de pratiques canadiennes] sert à orienter les mesures relatives aux normes minimales d'atténuation recommandées pour les levés sismiques effectués dans les eaux marines du Canada libres de glace. En raison des impacts d'origine anthropique et de l'évolution de la loi canadienne, il est nécessaire de passer en revue les politiques et les protocoles visant à réduire ces impacts au minimum. Le présent document de recherche s'efforce de déterminer si des seuils acoustiques quantitatifs peuvent être recommandés pour répondre aux besoins des espèces de cétacés inscrites et protégées en vertu de la *Loi sur les espèces en péril*. Si de tels seuils ne sont pas disponibles, il est alors question de seuils qualitatifs.

INTRODUCTION

Canada established the Species at Risk Act (SARA) in 2002 in recognition that species at risk needed legal protection to support conservation and recovery. Since 2002, efforts to refine and interpret the SARA have continued. Underwater noise, especially loud sounds, can negatively impact cetaceans through a number of mechanisms and is considered a potential threat to individuals and populations. At the same time, the offshore petroleum industry has shown a growing interest in oil and gas development in Canadian waters. Concerns have thus been raised about the potential impacts of oil and gas exploration and mapping activities on SARA-listed cetaceans, especially sounds produced by seismic airgun arrays during seismic surveys.

SPECIES AT RISK ACT DEFINITIONS

The *Species at Risk Act* (SARA) provides legislation for the protection of Canadian Species at Risk. The goal of the SARA is to prevent the extinction of endangered and threatened wildlife, to promote the recovery of these species, and to manage species of special concern to prevent them from becoming endangered or threatened (SARA 2002). SARA prohibits the killing, harm, harassment, capturing or taking of endangered or threatened individuals, or the destruction of their critical habitat:

> *"Section 32.(1) No person shall kill, harm, harass, capture or take an individual of a wildlife species that is listed as an extirpated species, an endangered species or a threatened species.*
>
> *Section 58.(1) No person shall destroy any part of the critical habitat of any listed endangered species or of any listed threatened species — or of any listed extirpated species if a recovery strategy has recommended the reintroduction of the species into the wild in Canada."*

(SARA 2002)

"Harm" is considered to be "*the adverse result of an activity where single or multiple events reduce the fitness (e.g., survival, reproduction, movement) of individuals*" (DFO unpublished[1]). "Harass" is considered to be "*any act or series of acts which tend to disturb, alarm, or molest and individual or population, which by means of frequency and magnitude results in changes to normal behaviour(s) that reduce an individual's ability to carry out one or more of its life processes which could jeopardize the survival or recovery of the species*" (most recent definition provided by DFO SARA Program, modified from the DFO (2009) definition of "harass" to incorporate results of recent supreme court decisions – see Provincial Court of British Columbia 2012). There is no formal SARA definition associated with the terms "capture" and "take", but these are likely the least applicable to seismic survey activities.

The SARA defines "critical habitat" as: *"the habitat that is necessary for the survival or recovery of a listed species and that is identified as the species' critical habitat in the recovery strategy or in an action plan for the species."* (SARA 2002). "Destroy" (or destruction of) critical habitat is "*determined on a case by case basis. Destruction would result if part of the critical habitat were degraded, either permanently or temporarily such that it would not serve its function when*

[1] DFO. 2013. The Operational Guidelines for the Identification of Critical Habitat for Aquatic Species at Risk. Draft – Please contact Species at Risk Program Management (NCR) to obtain a copy of this document.

needed by the species. Destruction may result from a single or multiple activities at one point in time or from the cumulative effects of one or more activities over time" (EC 2009). Thus, activities that prevent the function of critical habitat from being available when needed by the species would be considered to have destroyed critical habitat, even if the effect is temporary. While critical habitat is defined as a geo-spatial area, the availability of prey and other resources important to the fitness of listed species can be defined as a feature of their critical habitat and impacts on such features must be managed to maintain the functions of critical habitat (DFO 2010).

Because marine mammals utilize both the passive reception and active transmission of sounds for many important life functions, the ambient background noise levels of their habitat can enhance or reduce its suitability for these activities and changes in the acoustic environment of their critical habitat may reduce habitat quality and impact the fitness of listed species, thus the quality of the acoustic environment can be defined as a feature of critical habitat (EC 2009, DFO 2010). Activities that alter the acoustic environment of the critical habitat of listed cetaceans could result in destruction of critical habitat if its functions (e.g., providing foraging opportunities, supporting critical life history processes such as socializing, mating, giving birth to and rearing young) are either temporarily or permanently unavailable or compromised when needed. For example, if sounds produced during seismic surveys were to increase background noise within critical habitat known to be important foraging grounds for an at-risk species to levels at which individuals are no longer able to effectively forage (thus preventing them from accessing food within their critical habitat), then destruction of critical habitat would be considered to have occurred. It is therefore possible for sound-producing anthropogenic activities to alter the acoustic environment of the critical habitat to the extent that destruction of critical habitat occurs (DFO 2009).

Provided that specific criteria can be met; however, SARA allows activities that would otherwise be prohibited under the Act to proceed through the issuance of permits or agreements under Sections 73 and 74. SARA also allows exceptions for otherwise prohibited activities as outlined in Section 83 (SARA 2002). SARA does not currently provide specific guidance on sound exposure criteria or thresholds for harm or harassment of individuals, or for destruction of critical habitat.

SEISMIC AIRGUN SOUNDS

Seismic surveys are used to determine physical properties of the underlying geological structures of the seabed, the most common aim being the exploration for oil and gas deposits. Surveys tend to be episodic (or sporadic), lasting from days to months. A common survey tool is the airgun array acoustic source. Airguns generate sound by releasing high pressure air into the water. The airgun-generated pulse is characterized by a sharp rise followed by a rapid fall in pressure (Caldwell and Dragoset 2000). The acoustic spectrum is dominated by energy in the 10 to 120 Hz band, but contains significant energy to 1000 Hz (Goold and Fish 1998), and in some cases, measurable energy to 150 kHz (Goold and Coats 2006).

STATEMENT OF CANADIAN PRACTICE

Mitigation measures are required for seismic survey operations occurring in Canadian waters to reduce potential negative effects on marine mammals, including SARA-listed cetaceans. Since 2008, the Statement of Canadian Practice with respect to the Mitigation of Seismic Sound in the Marine Environment (SOCP) has been used to guide the minimum mitigation measures required for seismic operations occurring in all non-ice covered marine waters in Canada (DFO 2008).

Within the SOCP, it is specified that all seismic surveys must be planned to avoid significant adverse effects on individuals of marine mammal species listed as endangered or threatened (DFO 2008). While no specific guidance on sound exposure criteria or sound level thresholds to avoid such adverse effects is provided, several mitigation measures including avoiding displacement of or diverting individuals, establishing a minimum safety zone radius of 500 m around the seismic source, visually or acoustically monitoring this safety zone, and source ramp-up and shut-down procedures are recommended (DFO 2008). It is stated that "*Persons wishing to conduct seismic surveys in Canadian marine waters may be required to put in place additional or modified environmental mitigation measures, including modifications to the area of the safety zone and/or other measures as identified in the environmental assessment of the project to address species identified in an environmental assessment process for which there is concern*" (DFO 2008).

Project specific Environmental Assessments (EA), which are reviewed by offshore petroleum industry regulators, Fisheries and Oceans, Environment Canada, and other stakeholders, are conducted prior to seismic survey activities occurring in Canadian waters to determine if proposed mitigation measures are sufficient and to identify any additional measures needed. Member companies of the Canadian Association of Petroleum Producers and their seismic contractors have, at time, put into place additional mitigation measures identified during the EA process to further reduce the impacts of seismic survey activities on vulnerable species and sensitive marine areas (e.g., LGL 2013, 2014).

SEISMIC AIRGUN SOUND AND SPECIES AT RISK PROHIBITED IMPACTS

Sound is the primary sensory mode for marine mammals. They possess sound reception and production mechanisms highly adapted to sending and receiving acoustic signals within the aquatic environment (Richardson et al. 1995, Wartzok and Ketten 1999). Acoustic signals produced by marine mammals primarily serve social communication and/or environmental sensing (i.e., orientation and identification of objects through echolocation) functions (Richardson et al. 1995, Tyack 1999), or may potentially function to manipulate or herd prey (e.g., Janik 2000, Leighton et al. 2007). Because marine mammals have sensitive acoustic sensory systems, changes in the natural ambient acoustic environment could potentially negatively impact individuals and populations. It is widely recognized and accepted that underwater sounds from human activities have the potential to cause behavioural disturbance, physiological harm, and even death of marine mammals (Richardson et al. 1995).

LINKING POTENTIAL EFFECTS TO SARA-PROHIBITED IMPACTS

The SARA requires the protection of at-risk species by not killing, harming, or harassing individuals and by not destroying identified critical habitat (SARA 2002). DFO (2004) assessed potential effects/responses of seismic airgun sounds on marine mammals, but did not directly relate these effects to SARA-prohibited impacts. Here we hypothetically link these potential effects, with some modifications and additions, to the SARA-prohibited impacts "kill", "harm", "harass" and "destroy" (critical habitat) as defined above, by identifying direct and indirect consequences/impacts of each potential effect/response (Table 1). Although there remain many knowledge gaps about the potential impacts of seismic airgun sound on cetaceans and the likelihood of occurrence of SARA-prohibited impacts occurring during seismic survey activities is not well understood (DFO 2004), the effects/responses included here are commonly considered potential impacts for any noise-producing activity and therefore are also considered here as a potential impact of seismic airgun sounds. While Table 1 is based on the previous DFO (2004) study, it has been extended to meet an updated interpretation of the SARA

(DFO 2015). Modifications made to the potential effects provided by DFO (2004) and the links between these effects and the SARA-prohibited impacts are explained in the sections below.

There is overlap in some of the effects and consequences (for example, a change in behaviour is a potential consequence of many of the effects), but there are differences in the pathway between these effects and consequences (for example, auditory physiological effects may indirectly lead to reduced socializing or foraging due to loss of hearing, while displacement or migratory diversion may directly result in reduced socializing and foraging; Table 1). While few of the effects may directly result in killing of individuals, mortality can indirectly be linked to all of the physiological and behavioural effects. A direct link to harm can be made between all of the physiological and most of the ecological effects, while behavioural effects may be linked to harm through both direct and indirect pathways. Harassment is directly linked to all behavioural and some ecological effects, and indirectly linked to physiological effects. Only behavioural and ecological effects can be linked to destruction of critical habitat and in all cases, direct links can be made (Table 1).

IMPACT METRICS

Choosing appropriate seismic survey noise thresholds for avoiding SARA-prohibited impacts is difficult without well-defined criteria for these impacts that can be related to quantifiable and field-measurable metrics. In some cases, the impact is well understood, such as in the case of effects resulting in "kill" - the potential biological consequence to an effect would be the complete cessation of an individual's life functions. As another example, the impact criteria for "harm" resulting from "auditory physiological effects" could be a permanent hearing threshold shift (PTS). However, defining the appropriate impact criteria for "harassment" as a result of effects such as "changes in social behaviour" is much more difficult. The definition of such impact criteria for an individual, population, or critical habitat is not well understood in the literature and is beyond the scope of this document.

With an increased understanding of the criteria for SARA-prohibited impacts, appropriate impact metrics and acoustic thresholds can be developed and used to define acoustic thresholds within the SARA context. However, as further understanding of impact criteria are developed, the impact metrics and associated thresholds may need to change. For instance, an average sound pressure (root-mean-square or rms) level has been used as a metric for PTS in the past (NOAA 2000), but more recent efforts have focused on using a peak pressure level and a cumulative sound exposure level (SEL) (NOAA 2013). In some cases, impact metrics may be based on an indirect consequence of an effect. For example, temporary threshold shift (TTS) was not viewed by DFO (2004) as harm, nor does it fit under the DFO (2009) definition of "harm" in the SARA context. However, TTS may be an appropriate metric for impacts such as "reduced communication and echolocation efficiency."

There is a need for international standardization in acoustic terminology and measurement techniques, including an agreement in the metrics that may be used to characterize acoustic impact. BOEM (2012) indicated that *"… the current use of [underwater acoustical] terminology is inconsistent and not always appropriate*." And that "*A common terminology needs to be developed … that is useful and understandable to [acousticians, biologists and regulators].*" Working groups have been created by the American Nationals Standards Institute (ANSI) and the International Standards Organization (ISO) to develop standard terminology (ANSI 201x, and ISO 2007) and measurements (ISO 2012).

The following sections discuss impact criteria and metrics associated with the potential effects provided in Table 1, which could possibly be used to develop thresholds for SARA criteria.

OBJECTIVES

With further interpretation of the SARA, the generic recommendations provided in the SOCP should be evaluated in terms of avoiding SARA-prohibited impacts on listed cetaceans. The objective of this paper is to provide a discussion and recommendations for linking SARA-prohibited impacts to the SOCP with regard to received sound thresholds for cetaceans, specifically through addressing the following questions:

- Can quantitative thresholds for acoustic impacts from seismic surveys on at-risk cetaceans be recommended?
- Can qualitative thresholds for acoustic impacts from seismic surveys on at-risk cetaceans be recommended?
- Can a notional plan to determine quantitative or qualitative thresholds be recommended?

POTENTIAL EFFECTS ON MARINE MAMMMALS OF AIRGUN SOUNDS

PHYSIOLOGICAL EFFECTS

SARA-prohibited impacts related to physiological effects can be divided into auditory and non-auditory effects. Non-auditory effects include direct consequences with direct linkages to "harm" and indirect consequences which may be considered as "kill," "harm," or "harass" within the SARA context (Table 1). Auditory physiological effects can cause direct hearing loss which may result in direct "harm", but may also result in indirect consequences considered as "kill," "harm," or "harass" depending on the severity (Table 1).

Non-auditory physiological effects

Direct Consequences

DFO (2004) and Abgrall et al. (2008) concluded that it was unlikely for airgun sounds produced during seismic surveys (under field conditions) to cause non-auditory body tissue damage. Without contradicting this, Southall et al. (2007) and Cox et al. (2006) reported that non-auditory physiological effects might, in theory, include stress, neurological effects, bubble resonance, organ or tissue damage.

Little is known about the potential for airgun exposure to cause non-auditory tissue damage in marine mammals. However, it is known that high explosive detonations may result in marine mammal mortality or severe injury (Cameron et al. 1943; Wright 1951; Hanson, 1954; Wright 1971; Bebb and Wright (1952, 1953, 1954a, 1954b); Ketten et al. 1993; Ketten 1995). Parvin et al. (2007) provide a summary of the earlier results. For example, Cameron et al. (1943) showed high mortality rates of submerged monkeys, dogs, goats, and pigs when subjected to 145 kg TNT underwater detonation at ranges of up to 250 m. Airgun sounds have lower rise time and lower peak pressures than high-energy explosive detonations, suggesting that mortality or injury would only occur at very short ranges (directly next to an airgun array) (Parvin et al. 2007). Direct physiological effects such as tissue damage on beaked whales caused by acute sound exposure have been hypothesized as a possible indirect cause of mass strandings and mortality associated with naval medium-frequency active (MFA) sonars based on circumstantial evidence (Cox et al. 2006; Southall et al. 2007; Fernandez et al. 2005). However, there are indications that the tissue damage observed in these cases may be a secondary effect resulting from primary impact such as a behavioural response (Cox et al. 2006; Southall et al. 2007; Kvadsheim et al. 2012; Fahlman et al. 2014). Airgun sounds are different than MFA sonars in that the majority of the energy is broadband less than 1 kHz whereas the MFA sonar energy lies in narrow bands within the 1 to 5 kHz range (Hildebrand, 2009). The airgun sounds are too short, with energy spread over a relatively wide bandwidth, to excite the resonance effects (Jepson et al. 2003; Gentry 2002) and gas-bubble emboli growth (Crum et al. 2005; Fahlman et al. 2014) that have been hypothesized with MFA sonar.

Abgrall et al. (2008) supported the earlier conclusions by DFO (2004) that it was unknown if airgun surveys could contribute stress-related physiological change. Stress and anxiety are known to serve as a short-term defensive mechanism, and prolonged exposure can lead to chronic health impacts (Bateson, 2011). Wright and Kuczaj (2007) and Wright et al. (2007a; 2007b; 2009; 2011) showed that sound could be a source of stress in terrestrial animals and humans. Tyack (2008) showed that the terrestrial species knowledge could also be applied to cetaceans. Increased stress hormones have been linked to decreased reproductive success and well-being of marine mammals (Hildebrand 2005; Wright et al. 2007a, 2007b). Only Romano et al. (2004) specifically considered the stress-hormone change due to airgun sound exposure. The single airgun sound exposure was at a relatively low level but the nervous and immune system effects on the two individuals (one 32 year-old female *Delphinapterus leucas* and one 36 year-old male *Turisops truncates*) were minimal, but the effect was measurable. With the limited data and small sample size, the results do not easily lend themselves to the development of a quantitative acoustic threshold for increased stress hormone effects.

The lack of clear evidence on cause and effect makes it difficult to establish a metric to determine a quantitative acoustic threshold for direct non-auditory physiological effects resulting in SARA-prohibited impacts on cetaceans.

Indirect Consequences

Previous reviews (DFO 2004; Abgrall et al. 2008) concluded that airgun surveys were not likely to directly cause mortality of marine mammals through strandings. As mentioned above it is conceivable that documented strandings associated with MFA sonar may be an indirect consequence of a behavioural effect. An inappropriate change in diving and swimming patterns could possibly indirectly result in stranding and mortality. Though there has been a number of mass stranding events associated with MFA naval sonars, there is no unquestionable indication of such events associated with airgun usage. There are documented cases of strandings and deaths at sea (Castellote and Llorens 2013, Fernandez et al. 2005) that could be sometimes even precisely temporally and spatially linked with surveys in the Gulf of California (Hildebrand 2005),Brazil (Engel et al. 2004), and Liberia (Gray and Van Waerebeek 2011). However, special interest groups dispute these results (IAGC 2004; IWC 2007; Hogarth 2002; Yoder 2002). Notwithstanding the lack of unambiguous evidence, stranding events of beaked whales and other species associated with MFA sonars (D'Spain et al. 2006; Cox et al. 2006; Dolman and Simmonds 2006) create reason for concern for seismic survey operations.

DFO (DFO 2004; Abgrall et al. 2008) concluded that "it is unknown if exposure to seismic sound can result in changes in marine mammal social behaviour but if it were to occur there are conditions under which the worst-case consequences of such changes could be highly significant." Though only evidence of fatal non-auditory tissue damage exists, non-lethal tissue damage could theoretically result in changes in diet or foraging ability and therefore result in malnutrition. Malnutrition may be a logical indirect consequence of any impact that results in changes in the ability of an individual to find prey, such as changes in diving and respiratory patterns or reduced foraging.

As indicated above, it is possible that stress hormones may increase with exposure to airgun sounds which has been linked to decreased reproductive success (reduced fecundity) and well-being of marine mammals (Hildebrand 2005; Wright et al. 2007a, 2007b). Comparison of demographics of two beaked whale populations in and near the US AUTEC range in the Bahamas suggest lower productive rates for the population commonly found on the range (Claridge 2013). Energetic considerations due to the mammals leaving the range during naval active sonar exercises may have been a contributing factor. As in the Claridge (2013) dataset, such effects would require chronic exposure, which may not be the case for individual airgun surveys (McCauley et al. 2000b). Nieukirk et al. 2012 observed that cumulative seismic survey activities observed at the mid-Atlantic ridge cumulated to more than 80% days/month over a twelve month period. Though a single survey may not constitute an impact, the cumulative effect of multiple surveys may result in a situation similar to that observed by Claridge (2013).

Little additional information exists on indirect consequences of non-auditory effects. The linkage between non-auditory physiological effects, changes in social behaviour or foraging, and acoustic thresholds would need further investigation before quantitative thresholds could be established. The use of a model such as PCAD (Population Consequences of Acoustic Disturbances) (NRC 2005) or PCoD (Population Consequences of Disturbance) (Harwood 2013) would be required to link indirect non-auditory physiological effects to possible impact on the fitness and survival of an individual, then subsequently to population level consequences.

It may be difficult to find quantifiable acoustic thresholds for indirect consequences resulting from physiological effects. For instance, in this context, strandings could be an indirect impact of a physiological impact such as stress or tissue damage, but there are not enough clear cases linked to seismic surveys to determine thresholds.

Auditory physiological effects

Direct Consequences

Temporary or permanent hearing impairment is possible when marine mammals are exposed to high amplitude sounds (Goold and Coates 2006). Temporary threshold shift (TTS) is a short-term condition (lasting from minutes to days) occurring when animals are exposed to loud sounds, which may constitute injury in some contexts (Kryter 1985; Southall et al. 2007). TTS can cause unrecoverable neurological damage in at least in some terrestrial species (Kujawa & Liberman 2009). Without specific SARA consideration, DFO (2004) and Abgrall et al. (2008) state that TTS would be unimportant unless it resulted in a permanent threshold shift (PTS) or in hampering an individual’s ability to avoid other threats such as predators or entanglement in fishing gear.

Permanent hearing threshold shift (PTS)-based thresholds could likely be used for physiological effects resulting in killing of individuals and temporary hearing threshold shift (TTS)-based thresholds could likely be used for physiological effects resulting in “harassment” of individuals, but it was not clear if thresholds for physiological effects resulting in “harm” should be based on PTS or TTS. While PTS is used by other countries as a threshold for physical injury (e.g., NOAA 2013), the most recent definition of “harm” is not limited to physical injury and repetitive TTS could meet the SARA criteria for “harm” (Table 1). Further discussion is needed to determine if the thresholds for physiological effects resulting in “harm” should be PTS or TTS-based. A review of Southall et al. (2007), NOAA (2013) and any new scientific literature on PTS/TTS would likely provide the information needed to determine the most appropriate sound exposure metrics and associated thresholds for avoidance of physiological effects resulting in killing, “harm” and “harassment” of individuals. It is likely that several metrics and associated thresholds will be established for both PTS or TTS (for example, see Southall et al. 2007 and NOAA 2013).

Under current US National Marine Fisheries Service (NMFS) policy, Level A harassment (e.g. PTS) is deemed to occur if an individual animal is ensonified at a level higher than 180 dB re 1 μPa_{rms} (NOAA 2000). Proposed new guidelines (NOAA 2013) for TTS and PTS use dual criteria: peak pressure and cumulative Sound Exposure Level (SEL_{cum}). Three options for estimating the cumulative exposure are specified (1) a dynamic model including moving vessels and mammals with a cumulative dosage over the duration of the event; (2) a dynamic model including moving vessels and mammals with a cumulative dosage over a 24 h duration; or (3) a vessel and mammal static model with a cumulative dosage over a one hour (NOAA 2013). The SEL_{cum} is weighted by the species-dependent hearing (M-Weighted) and Equal Loudness (EQL) functions (NOAA 2013). For the M-Weighting, NOAA (2013) divide cetacean species into five broad functional hearing groups, three of which are relevant to cetaceans:

- Low-Frequency (LF) Cetaceans: Species with functional hearing in the 7 Hz to 30 kHz frequency band (baleen whales).
- Medium-Frequency[2] (MF) Cetaceans: Species with functional hearing in the 150 Hz to 160 kHz frequency band (dolphins, toothed whales, beaked whales including northern bottlenose whales).
- High-Frequency (HF) Cetaceans: Species with functional hearing in the 200 Hz to 180 kHz frequency band (true porpoise, pygmy and dwarf sperm whales).

Currently, only the LF and MF hearing groups are relevant for SARA-listed cetaceans. The LF and MF frequency definitions are different for the purposes of cetacean hearing groups and active sonar groups, and no standardized definitions are available. The NOAA (2013) draft guidance has extended the findings from Southall et al. (2007) (which is based on the most comprehensive scientific review of TTS and PTS in marine mammals to date and provides TTS and PTS thresholds) to include information available since 2007. The proposed TTS and PTS criteria are the minimum levels necessary to cause the hearing impairment.

The level at which PTS onset occurs is generally higher than that for TTS and has been estimated based on TTS studies. PTS results in permanent physical damage to the ear's hearing receptors, therefore controlled PTS experiments are avoided. PTS onset levels are predicted from TTS estimates based on the assumption that the relationship in cetaceans is similar to that for humans (NOAA 2013). TTS has been demonstrated and studied with captive animals (Southall et al. 2007; NOAA 2013), but no incidents of TTS or PTS associated with airgun sounds produced during seismic surveys have been published. Additionally, there have been no conclusive experimental studies that relate PTS to exposure of airgun sounds, though there is limited data on TTS onset with exposure to a single pulse from a seismic water gun (Finneran et al. 2002) and a small airgun (Lucke et al., 2009). The latter studies exhibited TTS at levels substantially lower than that recommended by Southall et al. 2007.

Figure 1 shows NOAA's (2013) the peak and SEL_{cum} threshold for TTS and PTS for each of the hearing groups assuming impulsive sounds consistent with previous DFO treatment.
NOAA (2013) also considers the case for non-pulsed sounds. Green and Richardson (1998) showed that while an airgun may produce pulsed sounds, the sound can become non-pulsed due to time-spreading or reverberation. Others (Simard et al. 2005; Clark and Gagnon 2006,

[2] The term medium frequency (MF) is not consistently defined in the literature. Hildebrand (2009) used 1 to 5 kHz as the frequency range of a MF active sonar. NOAA (2013) used a functional hearing range 150 Hz to 160 kHz when considering MF Cetaceans.

Cochrane, 2007, and Southall et al. 2007) have provided either data or argument to support the suggestion of treating the sound as non-impulsive in some cases.

Only the NOAA (2013) impulsive sound criteria will be considered for consistency with the previous DFO treatment. The peak level is a direct physical measurement, but the SEL_{cum} is weighted by the auditory weighting function shown in Figure 2. Combining Figure 2 with the SEL_{cum} criteria results in an unweighted criteria becoming frequency and species dependant as shown in Figure 3. That figure shows the unweighted frequency-dependant criteria for each of the hearing groups (NOAA 2013). The TTS and PTS minima for all cetacean hearing groups are plotted in Figure 4. Figures 2, 3 and 4 include grey areas for each of the airgun frequency bands described above. The majority of the energy is in the 0.01 to 0.12 kHz region, resulting in that band dominating the criteria for seismic surveys (Goold and Fish, 1998).

The criteria presented in Figure 4 could be used as a quantitative impact threshold for PTS and TTS for SARA-listed cetaceans. The figure shows the most conservative TTS criteria (i.e., the minimum threshold for TTS) for each of the airgun frequency bands. Note that the criteria changes with frequency, and the most conservative value is based on criteria for the frequency band that falls outside the frequency range where the most significant seismic energy occurs. Applying the minima from all frequencies would thus result in criteria that would be unrelated to the frequency band where the majority of the seismic energy lies. As indicated above, further discussion is needed to determine if the thresholds for physiological effects resulting in "harm" should be PTS or TTS-based. Implementation would require the specific airgun spectrum and acoustic transmission-loss conditions be used to determine the range of the effect.

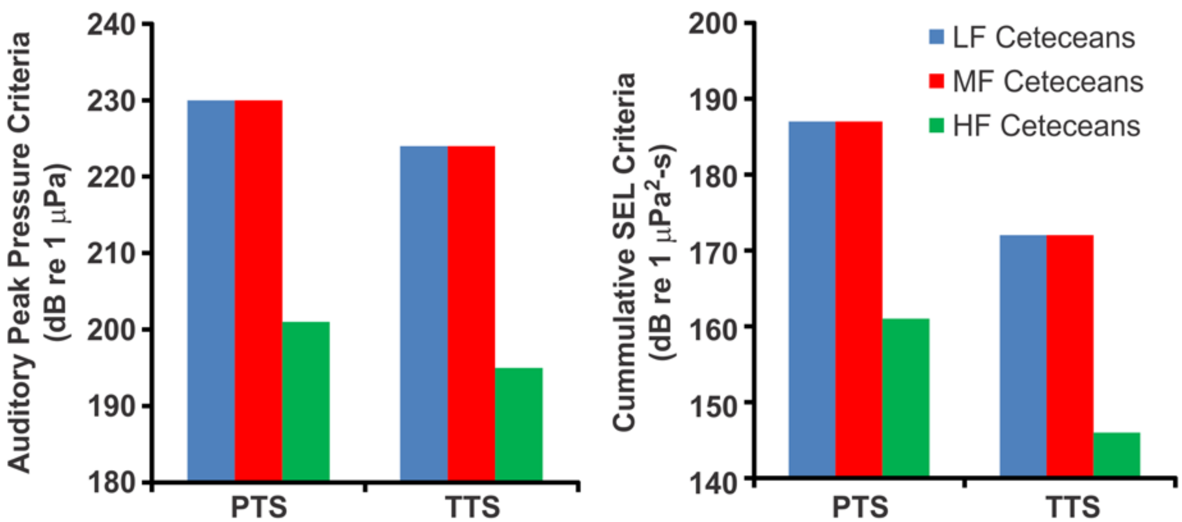

Figure 1: 2013 Draft NOAA PTS/TTS thresholds for impulsive sound sources (NOAA 2013).

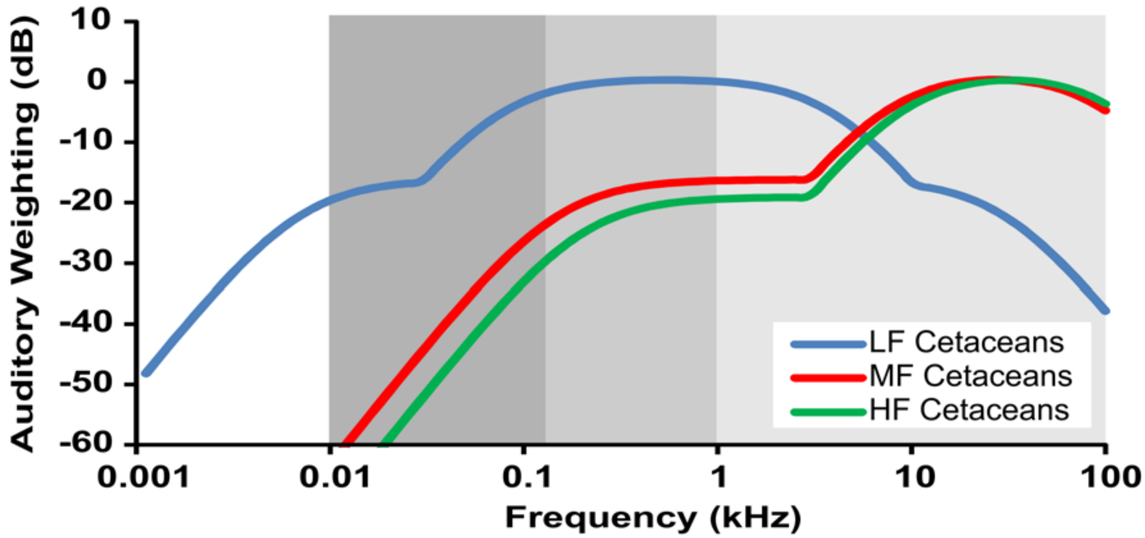

Figure 2: Frequency-dependant Hearing weight functions for low-frequency (LF), medium-frequency (MF), and high-frequency (HF) hearing cetaceans groups (NOAA 2013). Airgun spectrum (Goold and Coats 2006) (10 – 120 Hz, 120-1000 Hz, 1000-100000 Hz) indicated by different shades of grey background. The dominant frequency band is 120-1000 Hz with significant energy in the adjacent bands.

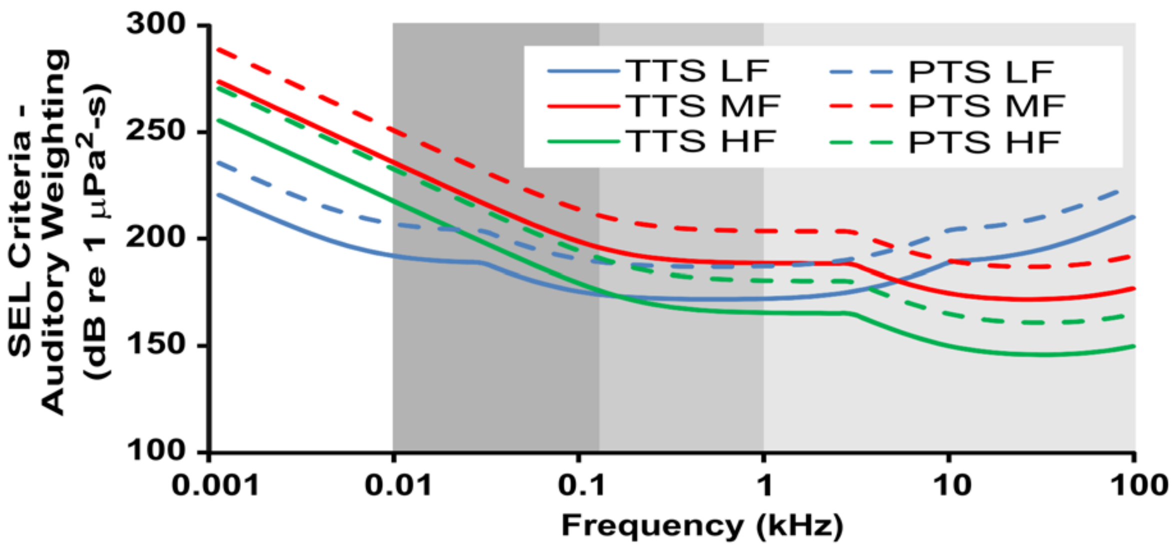

Figure 3: Cumulative sound exposure level minus hearing weight functions for Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) assuming an impulsive source. Results are included for High-Frequency (HF), Medium-frequency (MF) and Low-Frequency (LF) hearing cetaceans groups.

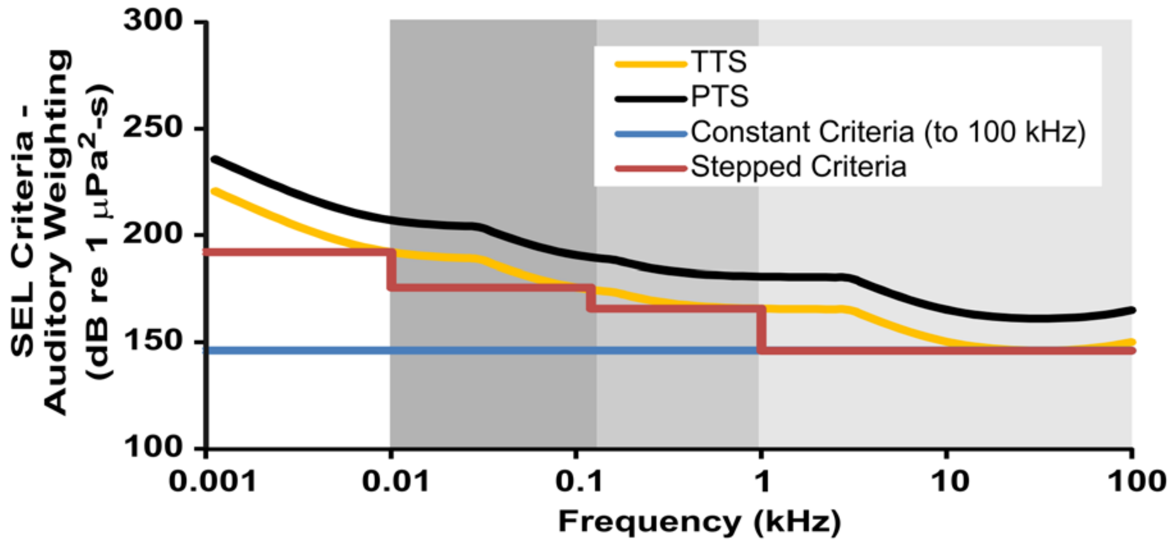

Figure 4: Minimum cumulative sound exposure level minus hearing weight functions for Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) assuming an impulsive source. Results are included for High-Frequency (HF), Medium-frequency (MF) and Low-Frequency (LF) hearing cetaceans groups. Airgun spectrum (Goold and Coats 2006) (10 – 120 Hz, 120-1000 Hz, 1000-100000 Hz) indicated by different shades of grey background. The dominant frequency band is 120-1000 Hz with significant energy in the adjacent bands. The most conservative criteria for TTS has been included for each airgun band and for the 1 Hz to 100 kHz spectrum.

Indirect Consequences

Theoretically, loss of hearing could result in a change of situational awareness and have a secondary impact on behaviour (such as foraging and socializing behaviour, which may be related to vocalizations). Such potential behavioural changes will be discussed under the behavioural changes section of this document.

DFO (2004) concluded that “it is unknown whether exposure to seismic sound can hamper the passive acoustic detection of prey by cetaceans”. It also concluded that “it is unknown whether exposure to seismic sound could increase the vulnerability of cetaceans to predators.” Abgrall et al. (2008) added that “No studies, either recent or older, have specifically examined the potential effects of seismic sound on the abilities of cetaceans to detect prey and/or predators.” Such consequences could indirectly lead from hearing loss but further work is required to connect hearing loss to changes in individual fitness and to impacts on life history through such indirect effects.

The linkage between hearing loss, the indirect consequences, and acoustic thresholds would need further investigation before quantitative thresholds could be established.

BEHAVIOURAL EFFECTS

Behavioural effects result in a cognitive change in activity as a result to sound exposure. These effects include changes in dive and respiratory patterns, social behaviour, vocalization patterns, time budget, displacement and migratory diversion and cognitive processes such as distraction. As with the physiological effects, each effect has direct and an indirect consequences which may constitute killing, harming or harassing individuals or destroying their critical habitat (Table1).

Changes in dive and respiratory patterns

Abgrall et al. (2008) supported the earlier DFO (2004) conclusions that sound from seismic airgun surveys can result in changes in dive and respiratory patterns in cetaceans, but that the significance of this impact is unknown. In worst-case scenarios, such changes may indirectly result in strandings and mortality, as discussed above.

Dive pattern changes have been observed for beaked whales in response to MFA sonar sounds (Tyack et al. 2011), but no airgun sounds were included in this study. Studies of sperm and western gray whales have investigated the response of cetaceans to seismic surveys. Reactions to seismic airguns can also be quite subtle and hard to detect. Tagged sperm whales in the Gulf of Mexico neither appeared to change direction nor demonstrated significant changes in diving behaviour when exposed to gradual ramp-up or the full-power of seismic airgun pulses at ranges of 1.5 to 13 km (Jochens et al. 2006). However, Miller et al. (2009) showed a case where one of eight sperm whales continued an abnormally long resting period (264 min) at the surface until the airguns ceased firing. The other animals showed no avoidance, but showed a reduced swimming effort during exposure. There were indications that prey capture attempts were 19% lower during airgun noise exposure. Miller et al. (2009) also indicate that these effects may be related to physical proximity to the airgun array rather than the received acoustic levels. Western grey whales visually observed showed no dive or respiratory pattern changes correlated with seismic airgun survey activities (Gailey et al. 2007).

Though a clear linkage between airgun sounds and changes in dive patterns currently cannot be made, it cannot be discounted as a potential effect. As with some of the previous effects, possible direct consequences of changes in dive and respiratory patterns include stranding, gas-emboli formation, increased energetic cost, and reduced socializing and/or foraging. The associated indirect consequences also include stranding/near-stranding/at-sea death, malnutrition, increased exposure to threats, and reduced reproduction and survival.

Further research is required on the behavioural response to airgun sounds and the relevance to harm and harassment within the SARA context. Hence, quantitative thresholds cannot be established at this time.

Displacement and migratory diversion

Abgrall et al. (2008) agreed with the DFO (2004) conclusions. The initial review concluded that "exposure to seismic sound can result in displacement and/or migratory diversion in some cetaceans, but this effect is species, individual, and contextually-related. The ecological significance of such effects is unknown, but there are conditions under which [the consequences of] the worst case scenarios could be high."

Studies of airgun survey impacts on marine mammals have been inconclusive with regard to displacement and migratory diversion. Factors such as species, maturity, experience, reproductive state, time of the day, and current activity may affect individual reaction (Wartzok et al. 2004; Southall et al. 2007). The biological significance of small displacements is unlikely to be significant (NRC 2005). However, chronic and/or larger-scale displacements may result in reproductive changes (Claridge 2013). Based on three ice-entrapment events, Heide-Jørgensen et al. (2013) proposed the possibility of a causal connection between ice entrapments and seismic surveys.

Stone and Tasker (2006) reported that the number of rorquals seen by observers on 201 seismic surveys off the United Kingdom were similar when airguns were active vs inactive, however, localized avoidance was observed. As well, all mysticetes were found at greater distances from the seismic vessels when they were active then when they were inactive, and during seismic shooting they appeared to remain longer at the surface where sound levels are lower. Reactions were stronger to larger volume seismic arrays (Stone and Tasker 2006). Moulton and Miller (2005) also reported the number of balaenopterid whales observed were similar when airguns were on vs off during seismic surveys near the Gully Marine Protected Area. Comparable results were also found by observers of blue, sei, and minke whales in the Orphan Basin and Laurentian Sub-basin (Moulton et al. 2005; 2006a; 2006b).However, Richardson et al. (1999), Miller et al. (1999), Moore and Angliss (2006), and Castellote (2012) documented mysticete avoidance of airgun surveys. For instance, Richardson et al. (1999) showed displacement of migrating bowhead whales as a result of ensonification at broadband received levels of 120-130 dB dB re 1$\mu Pa_{rms.}$ In other cases, mysticetes only showed very local avoidance and tolerated much higher exposure levels (Richardson et al. 1986).

Documented reactions to seismic surveys by odontocetes are varied but generally show avoidance (Jochens et al. 2006; Miller et al. 2006; Smultea et al. 2004; Moulton and Miller 2005; Bain and Williams 2006; Harris et al. 2007; Holst et al. 2006; Stone and Tasker 2006; Weir 2008a). Weir (2008b) documented varying responses of short-finned pilot whales to seismic airguns in operation during a ramp-up period including sharply turning away from the sound source, logging at the surface and orienting towards the sound source, and eventually swimming away in the opposite direction of the seismic vessel. Atlantic spotted dolphins were observed veering away from a ship during the early stages of a ramp-up off Angola (Weir 2008a). Weir (2008b) found that Atlantic spotted dolphins showed stronger responses to seismic airgun sounds than humpback or sperm whales. These dolphins were found significantly farther away from the airguns when they were on versus when they were off and only approached the seismic vessel when the airguns were silent. During their analysis of cetacean responses to 201 seismic surveys in UK waters, Stone and Tasker (2006) found that odontocetes exhibited evidence of disturbance. During active seismic surveying, all small odontocetes and killer whales were found at greater distances from the seismic vessel than when it was not shooting. Small odontocetes showed the greatest horizontal avoidance, which reached to the limit of visual observation. Sighting rates for sperm whales, pilot whales, and killer whales did not decrease when airguns were off vs. on, but killer whales showed localized avoidance. During seismic shooting, fewer animals appeared to be feeding and smaller odontocetes seemed to swim faster. Reactions were stronger to larger volume seismic arrays. Stone and Tasker (2006) theorized that smaller odontocetes may vacate the area entirely during exposure to seismic sounds, whereas slower-moving mysticetes may remain in the area, but increase their distance from the noise.

Displacement or migratory diversion can be theoretically linked to various consequences for individuals. Direct consequences of displacement and migratory diversion include increased energetic costs, and reduced socializing and foraging while possible indirect consequences of displacement include malnutrition, potentially increased exposure to natural threats, and reduced reproduction and survival (Table 1).

In agreement with the previous studies (DFO 2004; Abgrall et al. 2008), displacement and migratory diversion appears to be dependent on species, individual, and context. The application of the gray, bowhead, and humpback whale study results (160 dB re 1 μPa_{rms} criteria) is not justified as a criterion for odontocetes. Due to the high degree of variability and large knowledge gaps in cetacean reactions to seismic airgun sounds thresholds for avoiding displacement and migratory diversion cannot be proposed at this time.

Changes in social behaviour (excluding vocal behaviour)

DFO (DFO 2004; Abgrall et al. 2008) concluded that “it is unknown if exposure to seismic sound can result in changes in cetacean social behaviour, excluding vocal behaviour (which is discussed below), but if it were to occur there are conditions under which the worst-case consequences of such changes could be highly significant.” There are currently still no published studies directly related to this topic, so the previous conclusion can be neither supported, nor refuted.

Hypothesized direct consequences include reduced foraging while indirect consequences could include calf mortality, and reduced reproduction/survival. DFO (2004) concluded that “it is unknown if exposure to seismic sound can hamper parental care or bonding in cetaceans.” The later review (Abgrall et al. 2008) offered no change to the conclusion. There are currently no published studies directly related to the topic.

The linkage between changes in social behaviour, acoustic thresholds, and SARA harassment criteria would need further investigation before quantitative thresholds could be established.

Changes in vocalization patterns

DFO (2004) concluded that “it is known that exposure to seismic sound can result in changes in cetacean vocal behaviour, and when it occurs, there are conditions under which the worst-case consequences could be highly significant.” It also concluded that “it is unknown if exposure to seismic sound can result in reduced communication or echolocation efficiency in cetaceans.” The Abgrall et al. (2008) review concluded that the discontinuous nature of airgun survey pulses makes significant masking effects unlikely even for species with hearing overlap with seismic airgun spectra. However, in a reverberant environment, energy scattered from the seabed can spread the arrival in time, affectively raising the background noise level between airgun pulses (Simard et al. 2005; Clark and Gagnon 2006, Cochrane 2007). In Cochrane’s data, the reverberant energy at the receiver remained above the ambient noise level for 6s after the arrival of the direct path. Cochrane’s data set conflicts with the Abgrall et al. (2008) conclusion.

Many studies show a reduction, and sometimes increasing or cessation, in calling in the presence of seismic surveys (Clarke and Gagnon 2006; Di Iorio and Clark 2010; Richardson et al. 1986; McDonald et al. 1995; Greene et al. 1999a, 1999b; Nieukirk et al. 2004, 2012; Smultea et al. 2004; Holst et al. 2005a, 2005b, 2006, 2011; Dunn and Hernandez 2009; Cerchio et al. 2010).

Clark and Gagnon (2006) documented fin-whale calls stopping with the start of a seismic survey in the area. Di Iorio and Clark (2006) documented blue-whale call rates increasing in the presence of a seismic sparker source. The authors postulated that the blue whales were attempting to compensate for the additional introduction of noise, and noted that whales probably received a fairly low level of noise (131 dB re 1 µPa (peak to peak) over 30–500 Hz, with a mean sound exposure level of 114 dB re 1 μPa^2 s). Thus, they suggested that even low source level seismic survey noise could interfere with important signals used in social interactions and feeding (Di Iorio and Clark 2010). Castellote et al. (2012) documented fin whales lowering call rates with the introduction of airgun sounds. Around 250 male fin whales appeared to stop singing for several weeks to months during a seismic survey, resuming singing within hours or days after the survey ended (IWC 2007). McDonald et al. (1995) noted that a blue whale stopped calling in the presence of a seismic survey 10 km away. Blackwell et al. (2013) and Blackwell et al. (2015) showed an overall decrease in calling rates, but only after an initial increase correlated with the start of airgun shooting.

Odontocetes have been found to continue calling in the presence of airgun sources (Gordon et al. 2004; Madsen et al. 2002; Holst et al. 2005a, 2005b, 2006, 2011; Holst 2009, Hauser and Holst 2009, Tyack et al. 2003; Jochens et al. 2006). However, call rates may be reduced (Goold 1996; Smultea et al. 2004; Potter et al. 2007) or, in some cases, cease (Bowles et al. 1994; MacDonald et al. 1995) while airguns operate nearby. Much of the documented data (e.g. Holst et al. 2005a, 2005b, 2006, 2011; Holst 2009, Hauser and Holst 2009) showing continued calling does not provide insight into any call rate changes as baseline data was not collected.

Consequences of such effects include reduced socializing and foraging. As with other effects, malnutrition, reduced reproduction and survival could result as indirect consequences of changes in vocalization patterns. Though there is evidence to suggest a reduction in communication space, there is inadequate literature to suggest that an acoustic threshold could be proposed to represent an effect with consequences.

Changes in time budget

Changes in foraging or communication efficiency can lead to direct changes in time budgets. Purser and Radford (2011) considered the foraging efficiency for Three-Spined Sticklebacks (*Gasterosteus aculeatus*). For this fish species, acoustic noise affected the food-handling error rates and reduced food/non-food discrimination without significant impact on the total amount of the food taken. The result was a change in the time budget due to the foraging inefficiency.

With changes in time budget, an increased energetic cost is likely the direct consequence. It not known if this actually occurs in cetacean species.

Changes in cognitive processes

Changes in cognitive processes, such as distraction have been shown in non-cetacean species to reduce socializing, foraging, and increased predation risk (Chan et al. 2010; Purser and Radford, 2011). Bateson (2011) considered both masking and increased anxiety effects on decision making for cetaceans. Increased anxiety could result in an associated increase in risk aversion. Bateson asserts that increased risk aversion may have a short-term benefit, but chronic anxiety is likely to result in behavioural changes that may affect the health and fitness of the individual. Though theoretical publications are available for cetaceans, no published data documenting the effects specific to cetaceans could be found.

ECOLOGICAL EFFECTS

SARA-prohibited impacts related to ecology are related to effects that hamper the ability of the species to undertake important life functions. Based on the previous DFO (2004) analysis, these include hampered passive acoustic detection of prey, predators, and conspecifics; avoidance of anthropogenic threats (e.g., ship strikes, bycatch, etc.), and use of critical habitat/reduced occupancy. Table 1 presents the direct and indirect consequences for each effect including the relationship with the SARA terms: kill, harm, harass, and destroy.

Hampered passive acoustic detection of prey, predators, and conspecifics

DFO (2004) concluded that “it is unknown whether exposure to seismic sound can hamper the passive acoustic detection of prey by cetaceans”. They also concluded that “it is unknown whether exposure to seismic sound could increase the vulnerability of cetaceans to predators.” Abgrall et al. (2008) added that “No studies, either recent or older, have specifically examined the potential effects of seismic sound on the abilities of cetaceans to detect prey and/or predators.”

Abgrall et al. (2008) observed that “it is also unknown which, if any, species of cetaceans would use passive acoustic detection of prey as an important feeding strategy, with perhaps the exception of transient killer whales (Barrett-Lenard et al. 1996; Deecke et al. 2005). Although Abgrall et al. (2008) concluded that in general, masking by airgun signals is unlikely to have much effect on passive acoustic detection of prey, conflicting evidence suggests otherwise. As was discussed above, the impulsive airgun sounds may be temporally spread so that the periods between the direct arrivals still contain transmitted sound. Using a similar argument, the effect of such masking in hampering passive acoustic detection of predators and conspecifics is not known.

Direct consequences of hampered passive acoustic detection of prey, predators, and conspecifics include, but are not necessarily limited to predator-related injury/mortality; and reduced socializing/foraging. Indirect consequences could include malnutrition, increased exposure to threats, and, reduced reproduction/ survival.

Indicators for hampering passive acoustic detection of prey, predators and conspecifics may be similar to the reduced communication and echolocation efficiency and represented by a reduced communication space metric. As is the case with communication and echolocation efficiency, consideration should be given to using such metrics weighted by the auditory capability of the species as a potential threshold to address SARA criteria for destruction of critical habitat. The clear linkage between destruction of habitat and acoustic thresholds needs to be investigated before such quantitative criteria could be used within the SARA context.

Hampered avoidance of anthropogenic threats

The earlier DFO (2004) review concluded that “it is a concern that exposure to seismic sound could reduce the ability of cetaceans to avoid anthropogenic threats, but the risk has not been demonstrated.” Though not associated with a seismic survey, Wright et al. (2013) statistically showed that a naval exercise in combination with certain fisheries was correlated with higher rates of harbour porpoise strandings. The naval activities, by themselves were not correlated with strandings. The Abgrall et al. (2008) review “considering the reduced speed at which seismic survey vessels travel during periods of active seismic surveying (typically 4.5 to 5 knots), plus the extra noise that they emit relative to routine vessel traffic, the risk of lethal injury from a vessel strike, would be limited. However, if exposure to seismic airgun sounds causes TTS or (worse) PTS in cetaceans, this could lead to a reduction in their ability to detect and avoid approaching vessels.”

A clear linkage of hampered avoidance to temporary auditory impact (TTS) would need to be made before TTS onset could be used as quantitative criteria within the SARA context for hampered avoidance of anthropogenic threats.

Similar to hampered passive acoustic detection of prey, predators, and conspecifics, direct consequences of hampered avoidance of anthropogenic threats include, but are not necessarily limited to anthropogenic injury/mortality; and reduced socializing/foraging. Indirect consequences could include malnutrition, increased exposure to threats, and, reduced reproduction/survival.

Indicators for hampering avoidance of anthropogenic threats may be similar to the reduced communication and echolocation efficiency. The levels should be weighted by the auditory capability of the species and by the acoustic signature of the prey, and predators.

Hampered use of critical habitat/reduced occupancy

The DFO (DFO 2004; Abgrall et al. 2008) reviews concluded that no studies had been undertaken to examine the potential for seismic airgun surveys to have indirect effects such as a reduction in prey abundance. Studies of airgun pulse impacts on fish behaviour (McCauley et al. 2000a, 2000b; Wardle et al. 2001; Hassel et al. 2003; Slotte et al. 2004) have shown temporary changes, but have not provided conclusive evidence of prey reduction for fish-eating species. Thresholds for prey species mortality may be a more useful than prey behaviour, but would require further investigation and understanding before it could be used as a SARA destruction of habitat criteria. Specific metrics and thresholds would be needed to enable SARA implementation.

The direct consequences of hampering the use of critical habitat include reduced socializing, foraging, and may indirectly imply reduced fecundity and survival.

DISCUSSION

The objective of this paper is to provide a discussion and recommendations for linking SARA-prohibited impacts to the SOCP with regard to received sound thresholds for cetaceans. The questions laid out in the objectives are addressed in the following paragraphs.

Can quantitative thresholds for acoustic impacts from seismic surveys on at-risk cetaceans be recommended?

Possible sound exposure metrics that could be used to determine quantitative thresholds for avoiding SARA-prohibited impacts are included in Table 3. Potential sound exposure metrics do exist for a number of effects such as auditory physiological effects, changes in vocalization patterns, hampered passive acoustic detection of prey, predators and conspecifics, and hampered avoidance of anthropogenic threats. In most cases; however, standardized descriptors of these metrics used by the wider scientific community do not currently exist.

Single independent thresholds to meet the SARA requirements of avoiding “killing,” “harm” and “harassment” of individuals and “destruction” of their critical habitat could not be determined at this time. PTS could likely be used to establish a threshold for avoiding physiological effects resulting in killing of individuals and TTS could likely be used to establish a threshold for avoiding physiological effects resulting in “harassment” of individuals, but it was unclear if PTS or TTS-based thresholds should be used to avoid physiological effects resulting in “harm”. PTS and TTS-based thresholds only partially address the avoidance of SARA-prohibited impacts to individuals as these metrics are not appropriate for measuring behavioural and ecological effects that could potentially result in the killing, “harm”, or “harassment” of individuals. The significant knowledge gaps that remain on the effects of seismic airgun sounds on marine mammals and the broad definitions for the SARA terms “harm,” “harass,” and “destruction” of critical habitat make it challenging to determine the appropriate metrics and establish acoustic thresholds for avoiding SARA-prohibited impacts.

Can qualitative thresholds for acoustic impacts from seismic surveys on at-risk cetaceans be recommended?

Due to the lack of information, establishing scientifically-based quantitative thresholds for many of the effects discussed here is not possible. However, qualitative thresholds may be inferred. However, an inherent difficulty is that standardized descriptors of these metrics used by the wider scientific community do not exist. In particular, definitions associated with behavioural aspects are exceeding difficult to quantify. For there to be a behavioural effect, an individual must make a cognitive change in activity as a result to sound exposure. This may happen at the limits of signal detectability and the threshold may be below the ambient noise level. This would not be a useful threshold as it would imply to cease all anthropogenic activity that introduces sound into the marine environment.

More reasonable metrics and thresholds would be to consider metrics and thresholds associated with the causing a competing sound not to be detected. Consideration could be given to hampering communication and detection of predators, prey, and conspecifics as qualitative metrics. Thresholds based on loss in communication space could be determined.

Can a notional plan to determine quantitative or qualitative thresholds be recommended?

As discussed in the previous sections, there are large knowledge gaps related to this topic. Determination of physiological thresholds may be far easier than determination of behavioural or ecological impact thresholds. For that reason, studies on the application of existing physiological thresholds may be the most feasible. The following provides recommendations for next steps towards determining quantitative and/or qualitative thresholds:

- Determine which of PTS or TTS would be most appropriate for establishing thresholds for physiological effects that constitute “harm” of individuals under SARA. Conducting a critical review of the various PTS/TTS thresholds being used throughout the world, including an examination of differences in calculated range of effect for PTS/TTS may be useful for informing this discussion.
- Conduct a review of Southall et al. (2007), NOAA (2013) and additional new scientific literature on PTS/TTS in marine mammals to gather the information necessary to choose the most appropriate metrics for establishing quantitative thresholds for physiological effects resulting in killing, “harm” and “harassment” of individuals as required under the SARA.
- Conduct a review of non-temporary neurological harm of TTS such as studied for terrestrial species by Kujawa & Liberman (2009).
- Continue to investigate possible metrics for establishing acoustic thresholds for non-auditory physiological effects, changes in dive and respiratory patterns, displacement and migratory diversion, changes in social behaviour, changes in time budget, changes in cognitive processes and hampered use of critical habitat/reduced occupancy.
- Investigate how change/reduction in communication space relates to changes in vocalization patterns, hampered passive acoustic detection of prey, predators and conspecifics, and hampered avoidance of anthropogenic threats and determine the extent of change in communication space that would constitute “harm” and “harassment” of individuals or destruction of critical habitat.
- The airgun sounds have been treated as impulsive by DFO, while evidence suggests that due to time spreading or reverberation, in some cases, the gaps between the airgun shots is filled in with reverberated energy, suggesting that the sound received at an animal may not be impulsive. Treating the sound source as discrete types (for example, impulsive and non-impulsive) is justified and consistent with the literature (Southall et al., 2007) with regard to hearing loss. It would require analysis and modelling of received acoustic signals, but more importantly, the impact of the relationship between signal coherence and hearing recovery time. The effects on loss of communication space may be an easier metric to consider in this case. Similar to hearing loss, this would require analysis and modelling of received acoustic signals within each hearing group. This research will help develop the knowledge base required to determine acoustic

thresholds to meet the SARA criteria for “harm”, “harassment” and “destruction” of critical habitat.

- Continue to conduct behavioural response and environmental monitoring studies to improve our understanding of the direct effects/responses that may occur during seismic survey operations. Such studies should be designed so that frequency and magnitude of response (i.e. effect on vital rates and population-level impacts) in relation to noise level and distance from the sound source can be assessed. Additionally, the linkages between direct effects/responses and long-term impacts on habitat use, health, reproduction, survival and recovery remain a significant knowledge gap requiring further investigation. The importance of designing and conducting long-term studies of the population-level and ecological impacts of seismic noise on cetaceans is emphasized by results from Claridge (2013) and Nieukirk et al. 2012. This research will help develop the knowledge base required to determine acoustic thresholds to meet the SARA criteria for “harm”, “harassment” and “destruction” of critical habitat.

OTHER CONSIDERATIONS

The use of airgun arrays for seismic surveys are not the only source of sound which may impact SARA-protected species. Walmsley and Theriault (2011) discussed a wide variety of sound sources affecting the Scotian Shelf. Figure 5 (from Walmsley and Theriault, 2011) depicts the sources of sound associated with various parts of the acoustic spectrum. Published data for the Scotian Shelf (Piggot, 1964; Desharnais and Collison, 2001; Hutt and Vachon, 2004; Pecknold et al. 2010) has been overlayed showing up to 20 dB higher levels from shipping contributions. Note that it shows a wider spectral contribution from airguns than discussed above. There is overlap between the frequency band used by seismic surveys; ships and industrial activities; and ocean traffic. If sound exposure criteria were used in this frequency band, it should be compared to the sound exposure levels generated from other sources (such as shipping). As the ocean traffic has become part of the general “soundscape,” the potential impact of seismic surveys needs to be considered within this context and cumulative noise levels need to be computed. Figure 5 shows the general trend. It may be difficult to apply a behavioural threshold associated with animal perception, loss in communication space, or other masking impacts if the thresholds approach baseline (without anthropogenic contributions) ambient noise levels. In some cases, the ambient noise levels are dominated by sound from other anthropogenic sources.

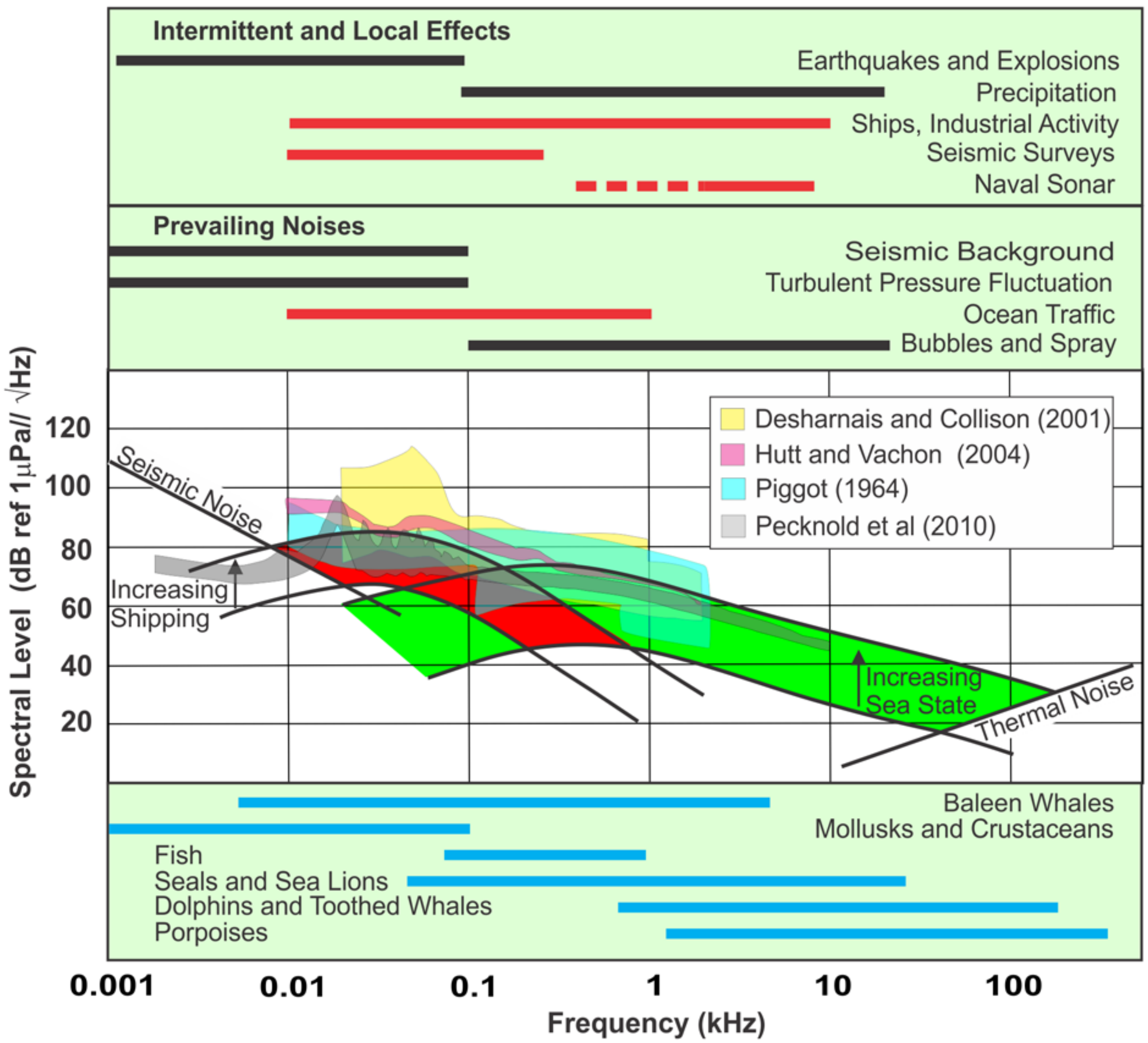

Figure 5: Scotian shelf noise from Walmsley and Theriault (2011).). The red "bars" and red area of the spectrum generated and dominated by man-made sound. The green area of the spectrum represents the natural level variation due to sea state.[3]

SUMMARY

DFO Science Sector was requested to identify sound exposure metrics and thresholds for seismic survey activities that could be used to avoid SARA-prohibited impacts on SARA-listed cetaceans.

Determining appropriate sound exposure metrics and associated thresholds to avoid SARA-prohibited impacts requires an understanding of the criteria that must be met through

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[3] Seismic Noise, as shown in Figure 5, is the result of naturally occurring activity in the seabed. This differs from the man-made noise generated by a seismic survey.

establishing such thresholds. For example, to establish an acoustic-based threshold for seismic survey activities to prevent “harm” to individuals, an understanding of what is “harm” (in the context of SARA), as well as the how the characteristics of sound relate to potential effects/responses that would constitute “harm” and thus need to be avoided, is necessary before an appropriate sound exposure metric can be chosen.

The potential effects (responses) of seismic airgun sounds on marine mammals were previously assessed by DFO (2004). These potential effects, with some modifications and additions, were hypothetically linked to the SARA-prohibited impacts “kill”, “harm”, “harass” and “destroy” (critical habitat) as defined above, by identifying direct and indirect consequences of each potential effect/response (Table 1).

A review of sound exposure metrics associated with each potential effect/response that could potentially be used to establish thresholds to meet SARA requirements was conducted (Table 2). Substantial scientific knowledge gaps made it difficult to determine appropriate sound exposure metrics for non-auditory physiological effects, changes in dive and respiratory patterns, displacement and migratory diversion, changes in social behaviour, changes in time budget, changes in cognitive processes and hampered use of critical habitat/reduced occupancy. It was determined that sound exposure metrics do exist (in that measurements that can be linked to the effect/response and the technology for making such measurements exist) for auditory physiological effects, changes in vocalization patterns, hampered passive acoustic detection of prey, predators and conspecifics, and hampered avoidance of anthropogenic threats (Table 2). However, in most cases, there are currently no standardized descriptors of these metrics used by the wider scientific community and it was not possible to determine a quantitative threshold for the potential effect/response in relation to SARA-prohibited impacts as they are currently defined without further research (e.g., behavioural response studies) as the amount of data available is limited. Threshold levels are also likely to be species and context specific, making the selection of appropriate thresholds even more challenging.

It was determined that data currently exist that could potentially be used to help establish quantitative thresholds for auditory physiological effects (Table 2). Permanent hearing threshold shift (PTS)-based thresholds could likely be used for physiological effects resulting in killing of individuals and temporary hearing threshold shift (TTS)-based thresholds could likely be used for physiological effects resulting in “harassment” of individuals, but it was not clear if thresholds for physiological effects resulting in “harm” should be based on PTS or TTS. While PTS is used by other countries as a threshold for physical injury (e.g., NOAA 2013), the most recent definition of “harm” is not limited to physical injury and repetitive TTS could meet the SARA criteria for “harm” (Table 1). Further discussion is needed to determine if the thresholds for physiological effects resulting in “harm” should be PTS or TTS-based. A detailed review of Southall et al. (2007), NOAA (2013) and any new scientific literature on PTS/TTS would likely provide the information needed to determine the most appropriate sound exposure metrics and associated thresholds for avoidance of physiological effects resulting in killing, “harm” and “harassment” of individuals. It is likely that several metrics and associated thresholds could be established for PTS or TTS (for example, see Southall et al. 2007 and NOAA 2013) that would meet the SARA requirements. Conceptually, the acoustic levels resulting physiological effects resulting in killing, harm, or harassment of individuals would be higher than behavioural effects; though the metrics may be quite different.

Change/reduction in potential communication space was suggested as a metric that could be used to establish a quantitative threshold for changes in vocalization patterns, hampered passive acoustic detection of prey, predators and conspecifics, and hampered avoidance of anthropogenic threats (Table 2), but again, quantitative thresholds could not be established due to limited available information.

It is important to note that because multiple potential effects/responses could be linked to any one of the SARA-prohibited impacts (Table 1) determining single independent acoustic thresholds for kill, “harm”, “harass” or “destroy” becomes difficult, as the metric chosen for any one threshold would need to be relevant for addressing a broad range of physiological, behavioural and ecological effects. Alternatively, it may be more appropriate to establish several thresholds that must be met to address the broad range of potential effects. For example, to prevent “harm” to individuals, it may be necessary to establish a threshold to address physiological effects (e.g., PTS/TTS), a threshold to address behavioural effects (e.g., change in vocalization rates) and a threshold to address ecological effects (e.g., change/reduction in potential communication space). Determining the potential effects/responses and associated sound exposure metrics most relevant for addressing each SARA-prohibited impact will require further discussion.

A number of research areas to address knowledge gaps relevant for establishing acoustic thresholds to meet SARA requirements and for evaluating the efficacy of the SOCP for avoiding SARA-prohibited impacts are provided above. To address knowledge gaps and better understand the impacts of seismic surveys on cetaceans, continued research efforts by the international science community aimed at increasing our understanding of the behavioural and physiological response of cetaceans to seismic airgun sounds, and the consequences of such responses on the habitat use, health, reproduction, survival and recovery of impacted individuals is needed. Finally, to fully evaluate the efficacy of the mitigation and monitoring measures implemented during seismic surveys for meeting SARA requirements, it will be necessary to design effective research programs with rigorous data collection protocols that allow for detection and quantitative analysis of potential negative impacts at ranges from the sound source where “harm”, “harassment” or “destruction” of critical habitat may occur, including beyond a defined safety zone.

As understanding and interpretation of SARA continues, revisiting the SOCP within the SARA context is recommended.

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Table 1. List of potential effects/responses (modified from DFO 2004) and potential impacts/consequences of seismic airgun sounds on marine mammal physiology, behaviour and ecology, and SARA-prohibited impact category to which they apply based on the most recent definitions. Examples of studies providing evidence of seismic airgun sounds causing a particular effect/response are provided. Under SARA-prohibited impact categories, black circles indicate a direct link between the potential effect and SARA-prohibited impact while grey circles indicate an indirect link between the potential effect and SARA-prohibited impact.

Potential effects/responses	Direct potential impacts/consequences	Indirect potential impacts/consequences	Kill	Harm[4]	Harass[5]	Destroy[6]
		Physiology				
Non-auditory physiological effects	Gas-emboli formation, organ/ tissue damage, neurological effects, increased stress hormones	Stranding/near-stranding/at-sea death, reduced socializing/foraging, malnutrition, reduced reproduction/survival	● (grey)	●	● (grey)	
Auditory physiological effects (*e.g.* . TTS, PTS) (Finneran et al. 2002)	Loss of hearing	Reduced socializing/foraging, malnutrition, starvation, increased exposure to threats, reduced reproduction/survival	● (grey)	●	● (grey)	

[4] Based on following definition of harm: "the adverse result of an activity where single or multiple events reduce the fitness (e.g., survival, reproduction, movement) of individuals" (DFO 2014).

[5] Based on following definition of harass: "any act or series of acts which tend to disturb, alarm, or molest an individual or population, which by means of its frequency and magnitude could reduce the likelihood of recovery or survival of the species by changing its normal behavior(s) and thus impacting a life history function" (unpublished report).

[6] Based on following definition of destruction of critical habitat: "if part of the critical habitat were degraded, either permanently or temporarily such that it would not serve its function when needed by the species" (EC 2009).

Potential effects/responses	Direct potential impacts/consequences	Indirect potential impacts/consequences	Kill	Harm[4]	Harass[5]	Destroy[6]
Changes in dive and respiratory patterns (Jochens et al. 2006; Gailey et al. 2007)	Stranding/near-stranding, gas-emboli formation, tissue damage, increased energetic cost, reduced socializing/foraging	Stranding/near-stranding/at-sea death, malnutrition, increased exposure to threats, reduced reproduction/survival	● (grey)	●	●	
Displacement and migratory diversion (Richardson et al. 1986; Miller et al. 1999; Bain and Williams 2006; Moore and Angliss 2006)	Increased energetic cost, reduced socializing/foraging	Malnutrition, increased exposure to threats, reduced reproduction/survival	● (grey)	●	●	●
Changes in social behaviour (*e.g.* . hampered parental care and bonding, hampered breeding, etc.)	Reduced socializing/foraging	Calf mortality, reduced reproduction/ survival	● (grey)	● (grey)	●	●
Changes in vocalization patterns (*e.g.* . hampered communication and echolocation) (Clark and Gagnon 2006; Di Lorio and Clark 2006; Castellote et al. 2012)	Reduced socializing/foraging	Malnutrition, reduced reproduction/survival	● (grey)	● (grey)	●	●
Changes in time budget (*e.g.* . proportion of time spent performing various activities such as resting, foraging, socializing)	Increased energetic cost, reduced socializing/ foraging/resting	Malnutrition, increased exposure to threats, reduced reproduction/ survival	● (grey)	●	●	●
Changes in cognitive processes (*e.g.* . distraction)	Reduced socializing/foraging	Malnutrition, increased exposure to threats, reduced reproduction/ survival	● (grey)	● (grey)	●	

Potential effects/responses	Direct potential impacts/consequences	Indirect potential impacts/consequences	Kill	Harm[7]	Harass[8]	Destroy[9]
		Ecology				
Hampered passive acoustic detection of prey, predators, and conspecifics	Predator-related injury/mortality, reduced socializing/foraging	Malnutrition, increased exposure to threats, reduced reproduction/ survival	●	●	●	●
Hampered avoidance of anthropogenic threats (e.g., ship strikes, bycatch, etc)	Anthropogenic injury/mortality	Increased exposure to threats, reduced reproduction/ survival	●	●	●	
Hampered use of critical habitat/reduced occupancy	Reduced socializing/foraging	Reduced reproduction/ survival				●

[7] Based on following definition of harm: "the adverse result of an activity where single or multiple events reduce the fitness (e.g., survival, reproduction, movement) of individuals" (DFO 2014).

[8] Based on following definition of harass: "any act or series of acts which tend to disturb, alarm, or molest an individual or population, which by means of its frequency and magnitude could reduce the likelihood of recovery or survival of the species by changing its normal behavior(s) and thus impacting a life history function" (unpublished report).

[9] Based on following definition of destruction of critical habitat: "if part of the critical habitat were degraded, either permanently or temporarily such that it would not serve its function when needed by the species" (EC 2009).

Table 2. Summary of information available and knowledge gaps to be addressed in relevance to determining the appropriate sound exposure metrics that could be used to establish thresholds for each potential effect/response of seismic airgun sounds on cetaceans.

Potential effects/responses	Potential sound exposure metric(s)	Information available	Knowledge gaps
		Physiological effects	
Non-auditory physiological effects	None determined	May be related to changes in dive and respiratory patterns. Currently no evidence of gas-emboli formation or hemorrhaging linked to seismic airgun sounds (DFO 2010). Increased stress hormone levels in cetaceans have been linked to increased vessel traffic and underwater noise levels (Rolland et al. 2012).	Probability of detecting physical injuries or at-sea deaths caused by seismic airgun sounds during offshore activities is low due to distance from shore, sinking carcasses and limited ability to respond to such incidents and perform necropsies in a timely manner. Currently no measurements of stress hormone levels in cetaceans during seismic surveys. Long-term impacts of increased stress hormone levels unknown but likely to include decreased immunity and fertility, as the stress response is highly conserved across species (Wright et al. 2007a,b)..
Auditory physiological effects (*e.g.* . TTS, PTS)	Metrics related to TTS, PTS (e.g., Sound Pressure Level (SPL), Sound Exposure Level (SEL), Cumulative SEL, Peak Amplitude)	Some information on TTS available, less information available on PTS (e.g., Southall et al. 2007). A variety of metrics have been used for establishing quantitative TTS/PTS thresholds (NOAA 2000, Southall et al. 2007, NOAA 2013).	PTS generally not empirically measured but derived from TTS. Thresholds for TTS/PTS based on a small set of measurements from a limited number of species.

Potential effects/responses	Potential sound exposure metric(s)	Information available	Knowledge gaps
		Behavioural effects	
Changes in dive and respiratory patterns	None determined	Some studies show changes in dive behaviour (e.g., fluke rate) and respiratory rate during seismic surveys (Abgrall et al. 2008).	Uncertainty in the most appropriate responses to measure (e.g., fluke rate, ascent/descent rate, dive duration, dive depth?) or how such responses relate to various sound exposure metrics. Responses variable and highly species/context specific, thresholds likely to be species dependent. Species-specific case studies examining frequency and magnitude of response needed. Long-term impacts of increased energetic costs unknown but can be estimated/calculated.
Displacement and migratory diversion	None determined	Some mysticete species known to move away from seismic activities (Miller et al. 1999, Moore and Angliss 2006), which likely have an energetic cost (Claridge 2013). However, in both, mysticete and odontocete species, the response is varied (Jochens et al. 2006; Miller et al. 2006; Smultea et al. 2004; Moulton and Miller 2005; Bain and Williams 2006; Harris et al. 2007; Holst et al. 2006; Stone and Tasker 2006; Weir 2008b).	Uncertainty in the most appropriate responses to measure (e.g., changes in swim direction, speed?) or how such responses relate to various sound exposure metrics. Responses variable and highly species/context specific, thresholds likely to be species dependent. Species-specific case studies examining frequency and magnitude of response (i.e. effect on vital rates and population-level impacts) needed. Long-term impacts of increased energetic costs unknown but can be estimated/calculated.

Potential effects/responses	**Potential sound exposure metric(s)**	**Information available**	**Knowledge gaps**
		Behavioural effects	
Changes in social behaviour (*e.g.* . hampered parental care and bonding, hampered breeding, etc.)	None determined	May be related to displacement, changes in vocalization patterns, hampered passive acoustic detection of conspecifics. It has been noted that mothers with calves are more sensitive to (respond to lower levels of) to seismic airgun sounds (McCauley et al. 2000).	Relationship between displacement and hampered parental care unknown. Uncertainty in the most appropriate responses to measure or how such responses relate to various sound exposure metrics. Responses likely variable and highly species/context specific, thresholds are likely to be species dependent. Species-specific case studies examining frequency and magnitude of response needed. Long-term impacts of generally unknown.
Changes in vocalization patterns (*e.g.* . hampered communication and echolocation)	Metrics related to changes/reduction in communication space	May be related to hampered passive acoustic detection of conspecifics and prey. Changes in vocalization patterns (e.g., increased/decreased vocalization rates, changes in call frequency, source levels) linked to seismic airgun sounds have been documented in some species (Clark and Gagnon 2006; Di Iorio and Clark 2010; Richardson et al. 1986; McDonald et al. 1995; Greene et al. 1999a, 1999b; Nieukirk et al. 2004, 2012; Smultea et al. 2004; Holst et al. 2005a, 2005b, 2006, 2011; Dunn and Hernandez 2009; Cerchio et al. 2010). Evidence of reduced communication space and masking as a result of seismic sound production exists, particularly important for low-frequency vocalizers (Clark and Gagnon 2006, Di Iorio and Clark 2006). This was noted as an important area to investigate due to wide-ranging impacts.	Uncertainty in how such responses relate to various sound exposure metrics. Responses variable and highly species/context specific, thresholds likely to be species dependent. Species-specific case studies examining frequency and magnitude of response are needed. Long-term impacts of changes in vocalization patterns and communication space generally unknown.

Potential effects/responses	Potential sound exposure metric(s)	Information available	Knowledge gaps
Behavioural effects			
Changes in time budget (*e.g.* . proportion of time spent performing various activities such as resting, foraging, socializing)	None determined		Not known if this occurs.
Changes in cognitive processes (*e.g.* . distraction)	None determined	Changes in cognitive processes due to anthropogenic noise have been shown to occur in some fauna. They result in hampering efficient foraging (Purser and Radford 2011), increased predation risk (Chan et al. 2010), but have been considered in general decision making for marine mammals (Bateson 2011)	Not known if this occurs in marine mammals.

Potential effects/responses	Potential sound exposure metric(s)	Information available	Knowledge gaps
		Ecosystem effects	
Hampered passive acoustic detection of prey, predators, and conspecifics	Metrics related to changes/reduction in communication space	May be related to auditory physiological effects. Because predators/prey make sound, some evidence that passive acoustic detection of predators/prey may be important for some species – e.g., beaked whale species have been observed responding to killer whale playbacks by leaving the vicinity (Tyack et al. 2011).	Not known if baleen whales passively acoustically detect prey. Uncertainty in how such responses relate to various sound exposure metrics. Long-term impacts of changes in communication space generally unknown.
Hampered avoidance of anthropogenic threats (e.g., ship strikes, bycatch, etc)	Metrics related to changes/reduction in communication space	May be related to auditory physiological effects and hampered passive acoustic detection. Some evidence that hearing impaired species increases vulnerability to ship strikes and entanglement (DFO 2004, Abgrall et al. 2008).	Links between exposure to seismic airgun sounds and increased exposure to threats uncertain.
Hampered use of critical habitat/reduced occupancy	None determined	May be related to hampered passive acoustic detection.	Not known if this occurs.

Table 3. List of potential effects/responses (modified from DFO 2004) and potential impacts/consequences of seismic airgun sound on marine.

Noise Exposure Critera	Positives/benefits/knowns	Negatives/limitations/ uncertainties	Research priorities
Noise Exposure Criteria			
SOCP - fixed range	Very easy to implement. Does not require acoustic modelling.	Does not easily equate to an acoustic criteria. No environmental dependencies. May not address TTS/PTS and therefore may not address harm/kill.	Determine if 500 m is adequate to prevent TTS/PTS under all possible sound source and environmental conditions.
NOAA 2000 Level A harassment thresholds (rms Sound Pressure Level)	Easy to implement/calculate.	May not be the correct metric (is it relevant for TTS/PTS). Only incorporates single sound exposure, ignores other factors. Need to get pulse rate right.	Model comparison study - calculate ranges of effect using various thresholds to see how range changes with varying thresholds and metrics.
NOAA 2000 Level B harassment thresholds (rms Sound Pressure Level)	Easy to implement	Same as NOAA Level A harassment, except longer ranges require more detailed modelling efforts.	Model comparison study - calculate ranges of effect using various thresholds to see how range changes with varying thresholds and metrics.
Southall et al. (2007) criteria	Probably the closest to representing the relevant metrics for hearing loss. Consistent with OHSA approach. Uses species dependant criteria.	Based on very small set of measurements. Dynamic models would be difficult to fold into "safety zone" concept. Requires the use of M-Weight/EQL Weight. Generalized functional hearing groups (does M-weight capture blue whale hearing range?).	Model comparison study - calculate ranges of effect using various thresholds to see how range changes with varying thresholds and metrics.
NOAA 2013 Guidance for PTS	Probably the closest to representing the relevant metrics for hearing loss. Consistent with OHSA approach. Uses species dependant criteria.	Based on very small set of measurements. "Potentially" complicated calculations involving agent models. Three methods proposed (1) 1 hour static (2) 24 hour dynamic and (3) event dynamic (could give you three different results). Dynamic models would be difficult to fold into "safety zone" concept. Ideally, requires the use of M-Weight/EQL Weight Generalized functional hearing.	Analysis of 2013 guidelines and criticism to guidance. Model comparison study - calculate ranges of effect using various thresholds to see how range changes with varying thresholds and metrics.

Noise Exposure Critera	Positives/benefits/knowns	Negatives/limitations/ uncertainties	Research priorities
	Noise Exposure Criteria		
NOAA 2013 Guidance for TTS	Probably the closest to representing the relevant metrics for hearing loss. Consistent with OHSA approach.	Same as NOAA 2013 Guidance for PTS. However, longer ranges likely to make predictions sensitive to animate behaviour.	Analysis of 2013 guidelines and criticism to guidance. Model comparison study - calculate ranges of effect using various thresholds to see how range changes with varying thresholds and metrics.
EU Pulse Days	Very easy to implement.	Does not easily adapt to SOCP. Could be used in environmental assessment and consideration of temporal/spatial avoidance.	
Vessel passages	Very easy to implement.	Not a direct physical or biological link between metric and impact. Does not easily adapt to SOCP.	